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DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
Panama City, Florida 32407

NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 13-80

MANNED EVALUATION OF THE PRE-PRODUCTION MK 16 UNDERWATER BREATHING APPARATUS

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The MK 16 Underwater Breathing Apparatus (UBA) was evaluated to assess its breathing characteristics, duration and technical characteristics at 150 FSW on N_2-O_2 and 300 FSW on He-O_2 in the Navy Experimental Diving Unit Ocean Simulation Facility Hyperbaric Chamber Complex. The oronasal pressures, inspired and expired oxygen and carbon dioxide, electronic oxygen control and failure warning system function were monitored. The results indicate that the oxygen alarms function well, breathing resistance is acceptable at both depths

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and the canister durations were adequate for mission support. The electronic control of oxygen was consistent, but the UBA is unreliable because of oxygen valve malfunction and erratic water-tight seal integrity. Additionally, the high negative static load experienced in the horizontal or head-down position caused extreme diver discomfort.

ABSTRACT

The MK 16 Underwater Breathing Apparatus (UBA) was evaluated to assess its breathing characteristics, duration and technical characteristics at 150 FSW on N_2-O_2 and 300 FSW on He-O_2 in the Navy Experimental Diving Unit Ocean Simulation Facility Hyperbaric Chamber Complex. The oronasal pressures, inspired and expired oxygen and carbon dioxide, electronic oxygen control and failure warning system function were monitored. The results indicate that the oxygen alarms function well, breathing resistance is acceptable at both depths, and the canister durations were adequate for mission support. The electronic control of oxygen was consistent, but the UBA is unreliable because of oxygen valve malfunction and erratic water-tight seal integrity. Additionally, the high negative static load experienced in the horizontal or head-down position caused extreme diver discomfort.

INTRODUCTION

The MK 16 is a closed circuit underwater breathing apparatus (UBA), functionally identical to the MK 15, but altered to meet the magnetic and acoustic requirements of the Explosive Ordnance Disposal (EOD) community. The major differences between the MK 15 and MK 16 are listed in Table 1. The MK 16 is designed to use nitrogen-oxygen breathing medium to depths of 150 FSW and helium-oxygen breathing medium to depths of 300 FSW. The breathing medium is maintained at a constant partial pressure of oxygen (P_{O_2}) by use of oxygen sensors that monitor and control the P_{O_2} via the battery-operated electronic module.

This report describes the results of a series of manned dives conducted at the Navy Experimental Diving Unit (NEDU) in the Ocean Simulation Facility (OSF) Hyperbaric Chamber Complex to evaluate the technical and life-support characteristics of the MK 16. Both graded exercise and carbon dioxide absorbent canister duration studies were done with the MK 16 instrumented so all aspects of its operating characteristics could be evaluated. In addition, calibration and set up procedures were critically analyzed.

MK 16 UBA Description

The MK 16 UBA designed to control the inspired P_{O_2} at 0.70 ± 0.10 ATA, has automatic mechanisms for adding or expelling gas volume to compensate for depth changes, and has displays which warn the diver when the P_{O_2} is outside the safe limits. The UBA is comprised of a breathing loop (Fig. 1) that contains the CO_2 absorbent canister, a flexible breathing bag with a port for addition of oxygen, a diluent gas addition valve to maintain adequate breathing bag gas volume on descent, an overpressure dump valve to vent gas during ascent, and, for this test, an AGA full face mask. The oxygen control mechanism has three oxygen sensors that monitor the P_{O_2} in the breathing bag and an integrated circuit electronics package that evaluates the sensor readings and operates a piezoelectric valve which adds oxygen as needed. Oxygen also may be added manually by depressing the oxygen add valve.

The UBA function monitoring system is comprised of a primary and a secondary display. The primary display consists of a red and a green light emiting diode (LED) mounted on the mask in the visual field of the diver. The green light should be on when the rig P_{O_2} is between 0.40 ATA and 0.90 ATA. A low oxygen alarm (flashing red LED) should initiate when the P_{O_2} falls below 0.40 ATA and a high oxygen alarm (flashing green LED) should initiate when the P_{O_2} exceeds 0.90 ATA. An electronics malfunction or low battery voltage is signaled by an alternating red and green flashing LED. The secondary display is a separately powered Liquid Crystal Display (LCD) which automatically scans and displays the three individual sensor millivolt outputs and battery voltage. The secondary display is located on an umbilical hanging from a front strap for easy access by the diver.

METHODS

The MK 16 evaluation was accomplished during two dive series; a 21-day saturation dive (NEDU Test Plan 80-4), and fourteen 150 FSW bounce dives (NEDU Test Plan 80-7) utilizing two preproduction model UBA's (PPM-1 and PPM-2). During the saturation dive, tests were performed to assess the CO_2 scrubbing characteristics (canister duration), and to evaluate the physical breathing characteristics of the UBA during graded exercise at depths of

150 FSW using N_2-O_2 and at 300 FSW using He-O_2 as breathing media. Tests on N_2-O_2 were conducted at 150 FSW because this is the current maximum operating depth based on decompression and nitrogen narcosis considerations. Both the canister duration and graded exercise studies were done in 40°F water. Additionally, canister duration studies were performed at 150 FSW in 70°F water to evaluate indications by unmanned studies of reduced canister duration in warm water (1). All 150 bounce dives used N_2-O_2 as the breathing medium, and were performed in 70°F water. These bounce dives were done to assess primary display function and limits of P_{O_2} control during rapid descents and ascents.

Thermal protection for dive subjects was provided by full neoprene wet suits during the 70°F water temperature studies, or by dry suits with undergarments during the 40°F studies. Diver work rate was provided by a specially designed electronically braked pedal mode ergometer (Warren E. Collins, Braintree, MASS.) modified for submerged use (2, 3). All studies were done with the diver in the prone position pedalling at a rate between 55-60 RPM.

Subjects

Six dive subjects were physically pre-conditioned by an 8 week program consisting of runs up to 4 miles per day and 30 minute graded exercises on a bicycle ergometer at work rates up to 200 watts, 5 days a week. During the conditioning and training period, the dive subjects underwent extensive training on MK-16 operation and set-up procedures. Many test pool dives simulating the activities planned for the experimental dives were performed so that a thorough familiarization with the MK 16 was achieved. Additionally, a series of 30 FSW bounce dives utilizing full instrumentation were performed to advance dive subjects' familiarization and assess data collection procedures.

Instrumentation

In the extensive instrumentation of the MK 16, it was insured that all parameters measured (Table 2) did not affect the normal operation of the apparatus. Data acquisition was accomplished by instrumentation leads replacing the normal MK-16 primary and secondary display leads. Parameters were either recorded on strip chart recorders (input impedance > 100K ohm) and/or by the HP-21 MX computer using a high impedance (> 10 M ohm) scanning voltmeter which sampled at four to five second intervals. The HP-21 MX recorded data on magnetic tape for future use, and also displayed the data in real time to allow rig monitoring during the dive.

Gas samples were obtained by low flow capillary sample lines (I.D. 0.86 mm) and micrometering valves with sampling rates of 300 to 700 cc/min Surface Equivalent Volume (SEV). The delay time from the rig to the mass spectrometer was less than 2 sec which provided rapid response to variations in gas composition without significant mixing in the sample line. The gas samples were analyzed by either a Perkin Elmer MGA 1100 or a Chemetron Model 7401 mass spectrometer. An accuracy of $\pm$ 0.01% was obtained by frequent calibrations during the experiments.

The oxygen storage bottle pressure was measured by a 3000 psi $\pm$ 1% Validyne DP 15 pressure transducer. This transducer was calibrated from 0-2500 psi against a Mensor 11600 digital pressure gauge (2500 psi $\pm$ 0.04%) before and after each study. A linear regression of Validyne voltage versus digital pressure gauge reading was calculated by the HP-21 MX computer. The Validyne output volts were then directly converted to pounds per square inch (psi) each time the computer sampled the pressure.

The inspiratory/expiratory pressure differential was measured at the oronasal mask by a Validyne DP-9 differential pressure transducer, referred to ambient water pressure at the level of the mask (Fig. 2). This transducer was calibrated by a water manometer before and after each study. Inspired gas temperature and rectal temperatures were measured by YSI 702 thermistor probes ($\pm$ 1.5°C). The ECG signal was conditioned by a tachograph which permitted either ECG or heart rate to be displayed.

Experimental Procedures: Bounce Dives

A series of fourteen 150 FSW dives with approximate 30 minute bottom times were conducted. These dives represented the maximum depth and bottom times allowable, using the currently available 0.70 ATA P_{O_2} in N_2 decompression algorithm (4). The dive profiles were controlled in real time by the HP-21 MX computer, which continuously monitored chamber depth from an Ascroft digigauge. The diver's decompression status was evaluated every 2 seconds with the depth and Safe Ascent Depth (SAD) continuously displayed.

Initial calibration of the MK 16, according to manufacturer procedures, was accomplished prior to the first bounce dive. The initial oxygen sensor millivolt readings on ambient air were used to establish a baseline. Calibration was checked prior to each dive on ambient air during the standard set-up procedure with recalibration being required only if the sensor voltage error was greater than 2 mv (10%) while exposed to ambient air.

During bounce dives, the MK-16 was set up and a fresh canister installed at the surface. The UBA was then connected to the instrumentation leads in the OSF and fitted to the dressed diver. The dive subject would enter the wet chamber and assume a prone position on the horizontal bicycle ergometer.

The chamber complex was then pressurized to 150 FSW at a rate up to 75 feet per minute (FPM). At 150 FSW, the dive subject either remained at rest or began alternating 6 minute, 100 watt exercise periods and 3 minute rest periods. When directed, ascent began at 60 FPM, with the dive subject maintaining the prone position during decompression stops. Dive subjects were instructed not to use the oxygen add or diluent add valve at any time except in an emergency or if instructed. Upon reaching the 20 FSW stop, checks of the high and low P_{O_2} alarms were performed. The dive subject was instructed to raise the P_{O_2} by operating the oxygen bypass valve until the high O_2 alarm activated or a maximum P_{O_2} of 1.80 ATA as determined from the mass spectrometer was reached. To check the low O_2 alarm, the dive subject was instructed to turn off the O_2 bottle supply and pedal the ergometer at 100 watts until the low O_2 alarm initiated or a minimum P_{O_2} of 0.25 ATA on the mass spectrometer was reached. Normal rig function was then resumed.

To evaluate the primary battery life and assess rig response to a low battery voltage, a freshly charged battery (6.4 volts) was installed before the first 150 bounce dive. This battery was used on several sequential dives without recharging until the P_{O_2} set point could no longer be maintained. After this experiment was completed, no dive was started with a battery voltage less than 6 volts.

Experimental Procedures: Saturation Dives

The 21 day helium-oxygen saturation dive was used to complete a series of 15 carbon dioxide absorbent canister duration studies and 12 graded exercise studies. The UBA's were initially calibrated on ambient air and then locked into the chamber complex. Baseline millivolt readings for all three O_2 sensors were recorded in chamber atmosphere. Because the P_{O_2} in the chamber atmosphere varied between 0.4 and 0.35 ATA, calibration factors were calculated which allowed normalization of the millivolt readings to the same P_{O_2}. This allowed the calibration to be checked in the chamber prior to each dive when absorbent canisters were changed. Recalibration was required if the normalized sensor millivolt readings differed more than 10% from the baseline.

Operational dives with the MK 16 using N_2-O_2 or He-O_2 will normally be conducted from the surface with the divers having dressed in air. To simulate this situation, and prevent the additional heat loss from the increased thermal conductivity of helium, the dive subject purged his dry suit of helium before entering the water. Purging was done by filling the suit with air and venting off three times. The suit exhaust gas was sampled the last time by the mass spectrometer sample line to insure the helium content was less than 5%.

To simulate the gas density normally encountered breathing N_2-O_2 for the 150 FSW studies, the dive subjects' lungs and UBA were purged of helium to a concentration less than 5%. This was achieved by having the dive subject breathe on an air SCUBA for 3 minutes prior to breathing the MK 16. If the UBA demonstrated a helium concentration of greater than 5%, the dive subject purged the UBA by repetitively inhaling from the rig, turning off the face mask shutoff valve, and then exhaling to the chamber atmosphere.

Canister duration studies were performed by having the dive subject perform alternating 6 minute 50 watt work and 4 minute rest cylces. The studies were to be terminated when the canister effluent P_{CO_2} exceeded 7.6 mmHg (1% SEV). Canister breakthrough was defined as the point when canister effluent P_{CO_2} exceeded 3.8 mmHg (0.5% SEV). Additional criteria for terminating a canister duration were rectal temperature drop of 1°C, fatigue or coldness of diver, time exceeding 6 hours, or rig failure. The graded exercises consisted of an initial 6-minute rest, followed by 6-minute work cycles of 50, 100, and 150 watts, separated by 4-minute rest periods.

Oxygen Consumption Measurement

The nature of the MK 16 provided an opportunity to measure oxygen consumption ($\dot{V}_{O_2}$) without additional instrumentation. For canister duration studies, $\dot{V}_{O_2}$ measurement provided a measure of total oxygen consumption and therefore (assuming a value for the $\dot{V}_{CO_2}/\dot{V}_{O_2}$ of 0.9) carbon dioxide production.

$\dot{V}_{O_2}$ was calculated by using the oxygen storage bottle pressure drop (ΔP_1), the known floodable bottle volume (2.868ℓ), and a temperture correction. This yields the equation:

$$\dot{V}_{O_2} = .1922 \frac{\Delta P_1}{t} \quad \ell/\text{min}$$

This yields the total oxygen consumed over the specified time period (Fig. 3).

RESULTS

Times required to reach canister breakthrough are listed in Table 3. Canister breakthrough time was defined as the mean of the individual times for the P_{CO_2} to reach 0.5% SEV (3.8 mmHg). The longest mean duration of 339 min was obtained at 150 FSW and 70°F. In 40°F water durations at 150 FSW and 300 FSW were 240 and 179 minutes respectively.

The $\dot{V}_{O_2}$ during the 50 watt work cycles was 1.48 $\ell.\text{min}^{-1}$ and during rest cycles was 0.48 $\ell.\text{min}^{-1}$. Based on mean $\dot{V}_{O_2}$ for the canister study, mean

$\dot{V}_{CO_2}$ was 0.98 $\ell.min^{-1}$ calculated multiplying the total O_2 consumed by the respiratory quotient of 0.9. Canister weights were also recorded for each dive. There was no correlation between either the diver's amount of CO_2 produced or canister weight and canister duration. Only three canister duration studies conducted in 40°F water were carried to breakthrough by a single dive subject. The other canisters required a dive subject change part way through the study because of termination criteria relating to a diver's condition, primarily hypothermia. Fig. 4 graphically depicts two typical canister duration curves. One canister was carried to completion by a single dive subject, with a duration of 267 minutes. The second canister curve demonstrates the regeneration that occurs during diver changeover. For this study, 17 minutes elapsed until the canister effluent P_{CO_2} for the first dive subject was reached by the second dive subject. This time was subtracted from the measured total time required to reach breakthrough yielding a corrected result of 171 minutes.

All 12 graded exercises were completed with the results compiled in Table 4. Fig. 5 shows a typical oronasal pressure recording, demonstrating the measurement of static oronasal pressure (static load) during a breath hold, and the pressure differential (ΔP) from full inspiration to full expiration. Note the static load during breath hold was -28 cm H_2O and Δ P was 24 cm H_2O. The generation of the static load is a result of the spatial relationship between the counterlung and the dive subject's mouth with its magnitude dependent on diver attitude. Fig. 2 depicts the counterlung design of the MK 16. The mask and hoses are semi-rigid, whereas the breathing bag is flexible and responsive to changes in ambient hydrostatic pressure. The bag pressure is transmitted through the hoses to the mask, making the pressure inside the mask equal to the average hydrostatic pressure at the level of the breathing bag. This means there is pressure in the mask equal to the difference between the hydrostatic pressure at the level of the bag and the hydrostatic pressure at the level of the mask. When the diver holds his breath, the mask pressure transducer measures this pressure difference (static load). Fig. 6 shows how diver position alters the static load. If the mask is below the level of the bag, a negative static load exists forcing the mask against the face of the diver. If the mask is above the bag, a positive pressure exists lifting the mask away from the face. All dive subjects in this study were in the prone position and the average static load was -29.5 ± 6.2 cm H_2O.

At a fixed flow rate, the oronasal ΔP is a function of total breathing loop resistance in the UBA. Fig. 7 represents the change in oronasal ΔP plotted against $\dot{V}_{O_2}$ for dives at 150 FSW and 300 FSW. There is a rise in ΔP with increasing $\dot{V}_{O_2}$ with a maximum ΔP of 20.5 ± 2.9 cm H_2O at 150 FSW and a $\dot{V}_{O_2}$ of 2.6 l/min. At 300 FSW, the maximum ΔP was 15.8 ± 3.4 cm H_2O at a $\dot{V}_{O_2}$ of 2.47 l/min.

The end tidal CO_2 is a measure of the effect of gas density and rig breathing resistance on CO_2 elimination. End tidal P_{CO_2} (mmHg) vs $\dot{V}_{O_2}$ is plotted in Fig. 8. The curve exhibits a sharp initial rise and a leveling off with a maximum level of 51 ± 8.0 mmHg CO_2 at 150 FSW, and 47.9 ± 7.6 mmHg CO_2 at 300 FSW, for the average maximum $\dot{V}_{O_2}$ of 2.6 l/min.

The pre-dive UBA calibration for both the bounce dives and the saturation dive was maintained within specifications ($\pm$ 10%) throughout the dives without requiring recalibration. The set point was assessed by noting the mass spectrometer P_{O_2} readings of the inspired gas every time the O_2 valve opened.

Table 5 tabulates the average set point and P_{O_2} when the valve closed for each dive with the range noted in parenthesis. There was no difference in performance between the two MK 16 rigs. The average set point for all the bounce dives was 0.73 ± 0.02 ATA and the P_{O_2} when the O_2 valve closed averaged 0.86 ± 0.02 ATA, yielding a nominal P_{O_2} range of 0.73 to 0.86 ATA. During normal O_2 addition cycles, brief transient spiking of inhaled P_{O_2} occurred (Fig. 9) because of streaming of O_2 into the inhalation line. The maximum values are listed in Table 5 with a mean value of 1.11 ($\pm$ 0.12) ATA. During bounce dive descents, air diluent is rapidly added to the system to maintain rig volume. This causes a marked rise in inspired P_{O_2} as shown in Table 5 with an average maximum of 1.44 ± 0.12 ATA.

During the bounce dives, there was an apparent compression effect on the set point control observed in all dives when an O_2 addition valve opening occurred during the first 12 minutes of the dive after compression (Table 6). On rest dives, there was often no addition of O_2 until the bottom time was completed because of the low $\dot{V}_{O_2}$ of the dive subject. In Table 6, the set point is tabulated for the different phases of the bounce dives. There is a significant lowering of the mean set points for the first 12 minutes (P_{O_2} = 0.68) compared to the mid portion of the dive (P_{O_2} = 0.73), or the late (decompression) portion of the dive (last 20 minutes). There is also an inconsistant set point shift during the late decompression phase.

The function of the primary display was assessed during the canister duration studies, graded exercises, and bounce dives. The mean P_{O_2} when the high O_2 alarm initiated was $0.92 \pm .01$ ATA. The mean P_{O_2} when the low O_2

alarm initiated was 0.46 $\pm$ 0.05 ATA. There was a brief transition period of an alternating red/green signal when changing from steady green to either the high or low O_2 alarm.

Fig. 10 depicts the time vs battery voltage discharge characteristics. The set point begins to decrease gradually when the voltage decreases to 5.6 volts, with approximately 65 minutes from first sign of failure (5.60 v) to the point where the rig will not maintain the P_{O_2} above 0.40 ATA (3.40 v). The low voltage alarm did not initiate until 4.7 volts was reached, about 45 minutes after the set point began to decrease. The total battery duration until reaching 5.6 volts was 17 hours for this battery. During the entire NEDU test series, several fully charged batteries failed in less than two hours for unknown reasons.

Both of the MK 16 UBA's experienced oxygen addition malfunctions during several of the dives. Referring to Fig. 9, note the shape of the addition phase with high peaks and the consumption phase with a relatively straight slope. Fig. 11 demonstrates a P_{O_2} tracing from a UBA with a malfunction of the piezioelectric O_2 valve. Note the ragged shape of the curve with an ill-defined and greatly prolonged addition phase. UBA PPM-1 demonstrated six isolated episodes of apparent O_2 valve malfunction. UBA PPM-2 demonstrated two successive days of intermittant partial opening of the O_2 valve, followed by a complete failure to open. It could not be demonstrated whether the malfunction was electronic failure or valve failure. This removed UBA PPM-2 from most of the saturation dive series. It is expected that under conditions of high O_2 consumption the partial opening valve would be unable to maintain proper O_2 levels.

Diver comfort utilizing the full face mask configuration proved to be a problem during the dive. The most significant problems were observed on dives of greater than two hours duration. Three of the six dive subjects experienced symptomatic face squeeze with eye redness, mild swelling around the eyes, nasal congestion, and runny nose during the canister duration studies. The negative static load caused the oronasal mask to collapse causing perioral discomfort. This effect was particularly prominent on bounce dives with the nose clearing device.

DISCUSSION

The requirement to minimize breathing loop resistance is based on the untoward physiological effects of a high breathing resistance. Adequate work performance at depth is limited by CO_2 elimination rather than oxygen supply for this UBA. The increasing measured inspiratory/expiratory pressure differential caused by increasing breathing resistance at a fixed P_{O_2} causes a concomitant decrease in effective pulmonary ventilation. A decrease in ventilation is accompanied by increased CO_2 retention (5), measured by elevation of end tidal CO_2. Carbon dioxide retention causes an array of undesirable physiological responses, which include increased susceptibility to decompression sickness, oxygen toxicity, inert gas narcosis, reduced exercise capability, and depression of central nervous system function (6). Measuring breathing resistance, in addition to inspiratory/expiratory ΔP, would require accurate flow rates. Since the flow rates are not available from this study, the breathing resistance can only be estimated by comparison to other UBA's under similar conditions of gas density and exercise. A specially designed low resistance underwater breathing apparatus has been

been used to demonstrate the physiological responses to breathing gas under hyperbaric conditions (7). From that study, the end tidal P_{CO_2} level reached at 6.70 ATA (188 FSW) on N_2-O_2, and a $\dot{V}_{O_2}$ of 2.50 liters/min, was 51 mmHg. The end tidal P_{CO_2} for similar conditions with the MK 16 was 50 mmHg. Comparison of these preproduction MK 16 UBA's with the parent MK 15 tested under similar conditions (8, 9) indicate that the newer apparatus is much improved and is certainly within an acceptable breathing resistance range.

The oronasal static load with the dive subject in the swimming position ranged from -20 to -42 cm H_2O with a mean of -29.5 ± 6.0 cm H_2O. Previous studies have shown that a slight positive pressure is preferred over negative pressure for breathing comfort. Negative pressure breathing in excess of -20 cm H_2O provides a 10 to 15% decrement in vital capacity and reserve volumes and may be a major cause of extreme dyspnea during severe exercise at depth (7). Using the MK 16, the dive subjects often endeavored to minimize the static load by assuming a more upright attitude on the horizontal ergometer (Fig. 6). No studies have been performed to assess the effect of such severe prolonged negative static load on the face or respiratory system. The negative pressure experienced caused the mask to be forced uncomfortably into the face with several dives resulting in a symptomatic face squeeze. The long term discomfort experienced would probably have an adverse affect on the performance of intricate manual skills by disruption of concentration.

The envelope of P_{O_2} control from 0.73 to 0.86 ATA is higher than the specified 0.7 ± 0.1 ATA. The 0.7 ATA set point was initially chosen as a convenient and safe level and the observed nominal elevation in inspired P_{O_2} poses no special problem, while providing an additional decompression safety factor. If desired, this can be altered by a simple recalibration.

Canister durations exhibited wide individual variability (Table 3) and decreased substantially with depth and cold temperature. Canister duration is affected by several factors, mainly ambient temperature and flow rate of gas through the canister (unpublished data from NCSC, 1979). The oronasal pressure tracings demonstrated wide variation in the respiratory pattern of the subjects. These individual variations may account for the variability of the canister duration times as one individual with a very erratic respiratory pattern had the two shortest canister durations of the series. The times achieved were adequate for mission support (Test and Evaluation Master Plan Number 765-1, UBA EX-16). Using the mean canister duration times minus one standard deviation provides an operational limit of 202 minutes at 150 FSW in 40°F water temperature. However, in the cold studies, the canister duration was longer than diver duration. The inadequacy of thermal protection does not permit full utilization of the current duration capabilities of the MK 16.

The mechanical function of the UBA, while satisfactory in most circumstances, was discrepant in some areas. The primary display signal and alarms functioned properly for the oxygen control criteria. However, the low battery voltage signal (Fig. 10) should initiate prior to 5.6 V to give adequate warning of UBA failure. The battery life and reliability of batteries, other than the one tested, was erratic and unpredictable. This could prove to be a major discrepancy in decompression diving and mission performance. The piezoelectric valve malfunction provides another problem. The nature of the valve mechanics does not provide the diver with means of adequately checking the valve function in the pre-dive set up procedures. The valve, if only partially opening, could appear normal in the pre-dive set up, but would be unable to supply adequate oxygen at high work rates. This could operationally prove to be a considerable hazard. There is currently no method to evaluate proper valve function. Otherwise, the calibration and set up procedures appeared to be adequate. The breathing bag will vent sporadically and without warning with changes in diver depth or attitude. This could prove to be an unacceptable hazard working in proximity to acoustic mines. Several UBA floodouts were experienced during the dive series for a variety of seal defects causing these dives to be aborted. If these floodouts were experienced in open water dives, serious injury could be expected.

In summary, the electronics control package and sensor system functioned adequately; but overall, the rig is unreliable because of battery failures, piezoelectric valve failure, and erratic watertight seal integrity. The canister durations at both 150 FSW and 300 FSW in 40°F water were adequate for mission support and much greater than the diver duration due to present day inadequate thermal protection. Diver thermal protection is not sufficient to adequately exploit the duration capabilities of the UBA. The 70°F conditions improved the canister duration and the dive subjects were able to complete an entire canister study. The breathing resistance of the UBA is acceptable, but the high negative (static load) pressures experienced in the horizontal and head-down position over long periods caused extreme discomfort to the dive subject.

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TABLE 1

COMPARISON OF MK 15 AND MK 16 UBA's

MK 15	MK 16
Standard Materials	Non-Magnetic Materials
Compression O-Ring Seals	Barrel O-Ring Seals
Printed Circuit Boards	Integrated Circuit Control Unit
Solenoid 0_2 Valve	Electronic Piezeoelectric Valve (Noiseless)
Alkaline Batteries	Rechargable Lead Acid Gel Batteries
Mouthbit and Mask	AGA Full Face Mask With Oronasal
0_2 Control	
Primary Display: six light direct readout	Primary Display: two light (LED) Logic Mode Mounted on Mask
Secondary Display: meter	Secondary Display: LCD

TABLE 2

PARAMETERS MEASURED

Parameter Measured	Test Series: 150 Bounce	150/300 Saturation: Canister Duration	150/300 Saturation: Gr. Ex.	How Recorded
Time	X	X	X	CS
Sensor Millivolts	X	X	X	CS
Canister Outlet P_{O_2}, PCO2	X	X	X	CS
Oronasal P_{CO_2}, P_{O_2}		X	X	S
Canister Inlet P_{CO_2}, P_{O_2}		X	X	S
O_2 Bottle Pressure	X	X	X	CS
O_2 Valve Function	X	X	X	C
Battery Voltage	X	X	X	C
Primary Display (LED) Function	X	X	X	CS
Canister Weight	X	X	X	N
Depth	X	X	X	C
Wet Pot Temperature		X	X	C
Inspired Gas Temperature		X	X	CS
ECG or Heart Rate		X	X	CS
Oronasal Inspiratory/ Expiratory ΔP		X	X	S
Diver Rectal Temperature		X		C

C = HP 21 MX Computer
S = Strip Chart
N = Separate Notation

TABLE 3

CANISTER DURATION RESULTS

150 FSW; 40°F Water Temperature; N_2-O_2

DIVE	Time*	Time to 1% SEV (Min)
01	251	
02	186	240
03	237	
04	300	
05	244	
06	219	
Mean	240 ± 38	

150 FSW; 70°F Water Temperature; N_2-O_2

DIVE	Time*	Time to 1% SEV (Min)
01	375	
02	267	315
03	362	
04	354	
Mean	339 ± 49	

300 FSW; 40°F Water Temperature; He-O_2

DIVE	Time*
01	171
02	172
03	184
04	202
05	166
Mean	179 ± 14

*Time to reach average inspired P_{CO_2} of 3.8 mmHg (.5% SEV)

TABLE 4

GRADED EXERCISE RESULTS

Depth/Gas	Work Rate (watts)	O_2 Consumption ($\ell \cdot min^{-1}$)	Mean Inspiratory/ Expiratory ΔP (cm H_2O)*	End Tidal CO_2 (mmHg)
150 FSW/ N_2-O_2	Rest	.48 ± .15	7.3 ± 2.7	36 ± 2.9
	50	1.48 ± .33	10.8 ± 3.7	47 ± 5.0
	100	1.8 ± .27	14.5 ± 5.1	49 ± 5.0
	150	2.64 ± .41	20.5 ± 2.9	50 ± 8.0
300 FSW/ He-O_2	Rest	.46 ± .07	7.5 ± 2.0	33 ± 4.6
	50	1.30 ± .12	9.3 ± 1.0	43 ± 6.1
	100	1.87 ± .18	11.3 ± 1.6	48 ± 7.6
	150	2.47 ± .34	15.8 ± 3.4	48 ± 7.6

*Average static loading pressure for all dives - 29.5 ± 6.0 cm H_2O

TABLE 5

150 FSW BOUNCE DIVE OXYGEN CONTROL(ATA)

	P_{O_2} when O_2 valve opened [avg(min,max)]	Max P_{O_2} when valve closed [avg(min,max)]	Max P_{O_2} Attained	
			During O_2 Addition	On Descent
1	.71(.67,.74)	.82(.79,.84)	.98	1.30
2	.70(.66,.74)	.82(.71,.90)	1.04	1.56
3	.74(.71,.76)	.89(.82,1.00)	1.32	1.20
4	.74(.68,.81)	.87(.80,.91)	1.03	1.51
5	.76(.72,.79)	.88(.74,.95)	1.01	1.48
6	.74(.66,.80)	.86(.76,.90)	1.14	1.40
7	.74(.70,.79)	.88(.83,.96)	1.09	1.48
8	.72(.70,.74)	.87(.80,.99)	1.32	1.35
9	.74(.69,.78)	.86(.81,.91)	1.13	1.57
10	.74(.69,.80)	.87(.74,.92)	1.04	1.55
OVERALL AVERAGE ALL DIVES	$.73 \pm .018$(.66,.81)	$.86 \pm .024$(.71,1.00)	$1.11 \pm .12$	$1.44 \pm .12$

TABLE 6

COMPRESSION EFFECT ON SET POINT

DIVE/RIG		Set Point (P_{O_2} when O_2 valve opened) ATA 0-12 MIN	MID DIVE	LAST 20 MIN
001/1	Work	.675	.716	.718
002/1	Work	.66	.71	.723
003/1	Work	.68	.732	.803
004/2	Work	.70	.783	.713
009/1	Rest	---	.74	.74
013/1	Rest	---	.726	.770
014/2	Rest	---	.710	.723
015/2	Rest	---	.750	.719
016/1	Rest	---	.733	.784
Avg.		$.68 \pm .017$	$.733 \pm .023$	$.743 \pm .033$

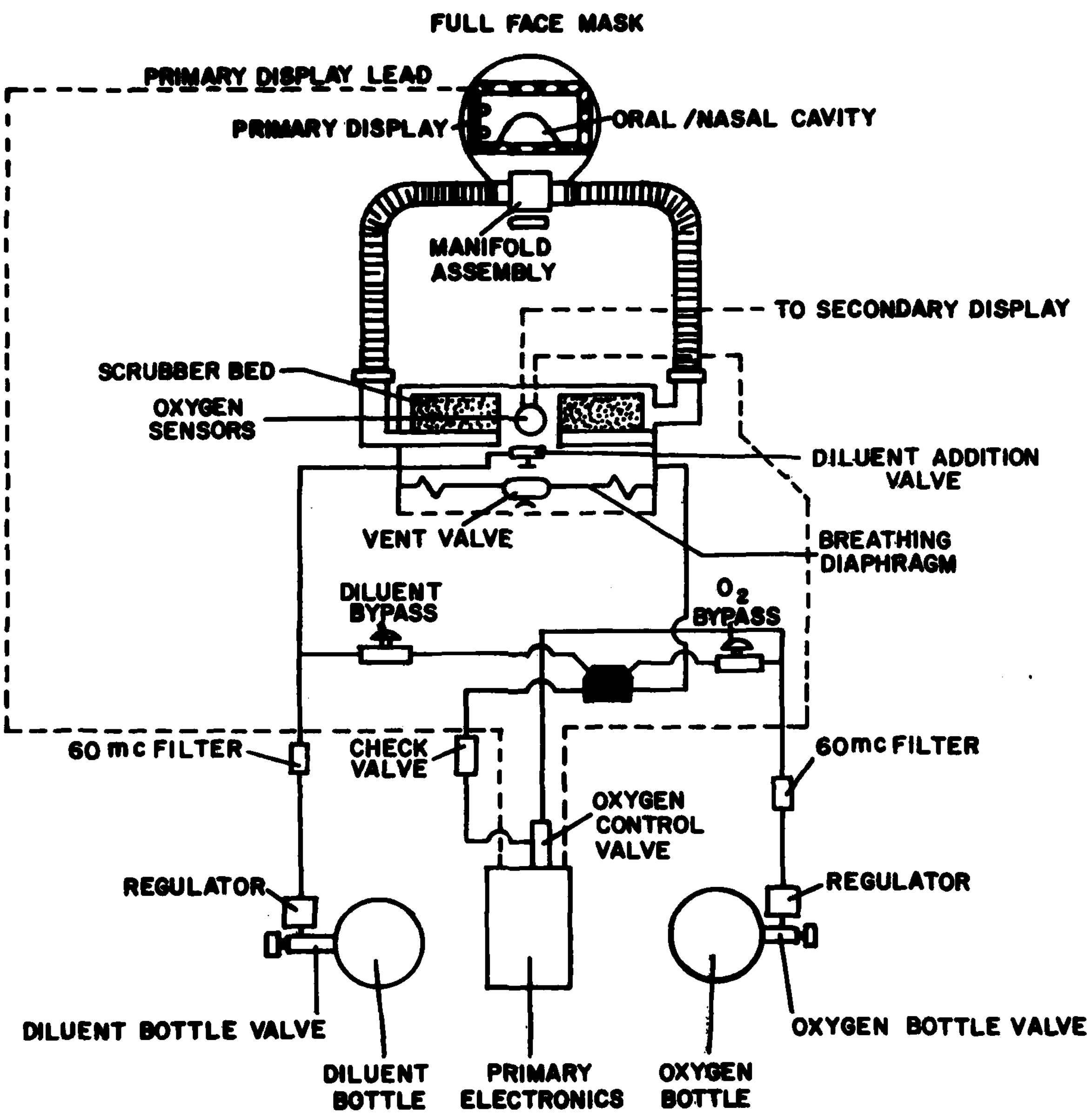


FIGURE 1. MK. 16 PNEUMATICS SCHEMATIC DIAGRAM.

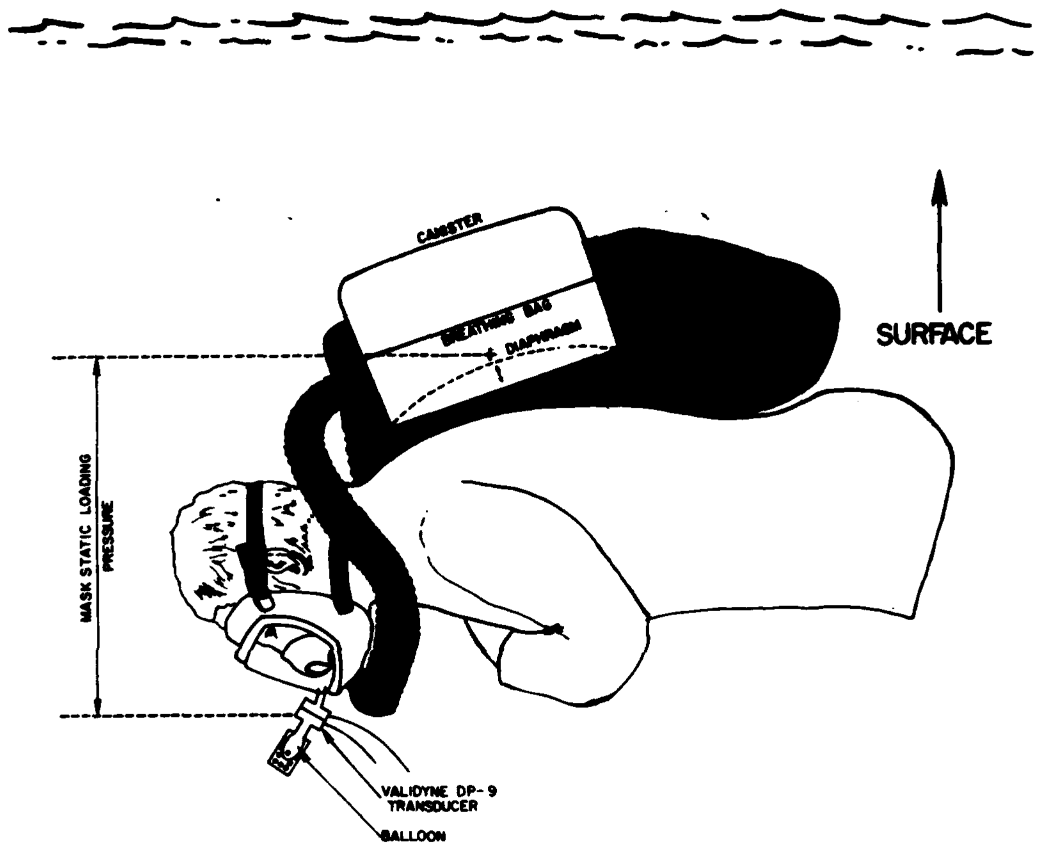


FIGURE 2. ORONASAL BALLOON AND PRESSURE TRANSDUCER, WITH DIVER IN PRONE SWIMMING POSITION.

FIGURE 3. O_2 BOTTLE PRESSURE DROP VS. TIME FOR COMPUTATION OF $\dot{V}O_2$. TYPICAL GRADED EXERCISE WITH SUPERIMPOSED WORK RATE

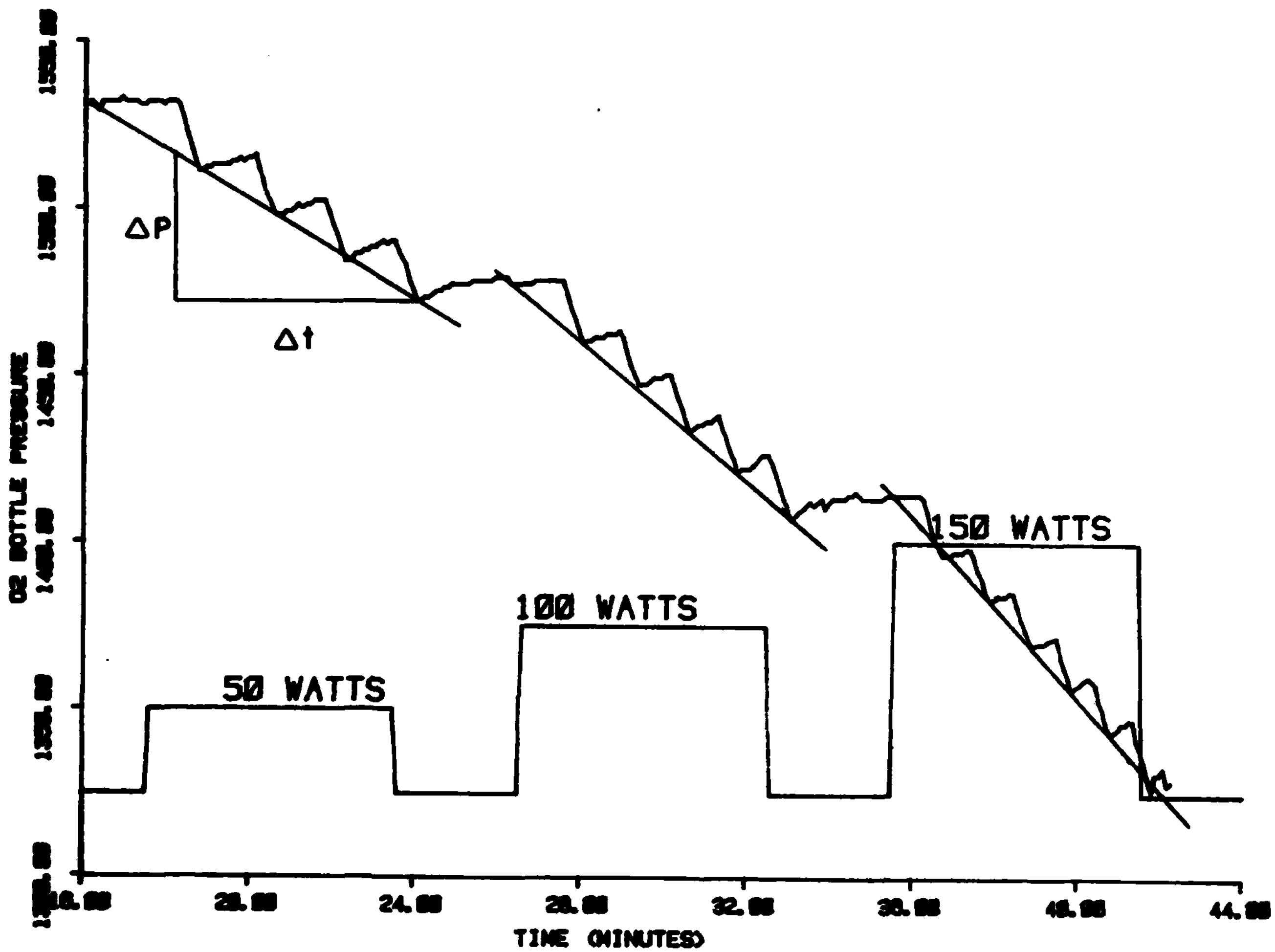


FIGURE 4. TYPICAL CANISTER DURATION GRAPHS FOR N_2-O_2 150 FSW 70° F AND He-O_2 300FSW 40° F

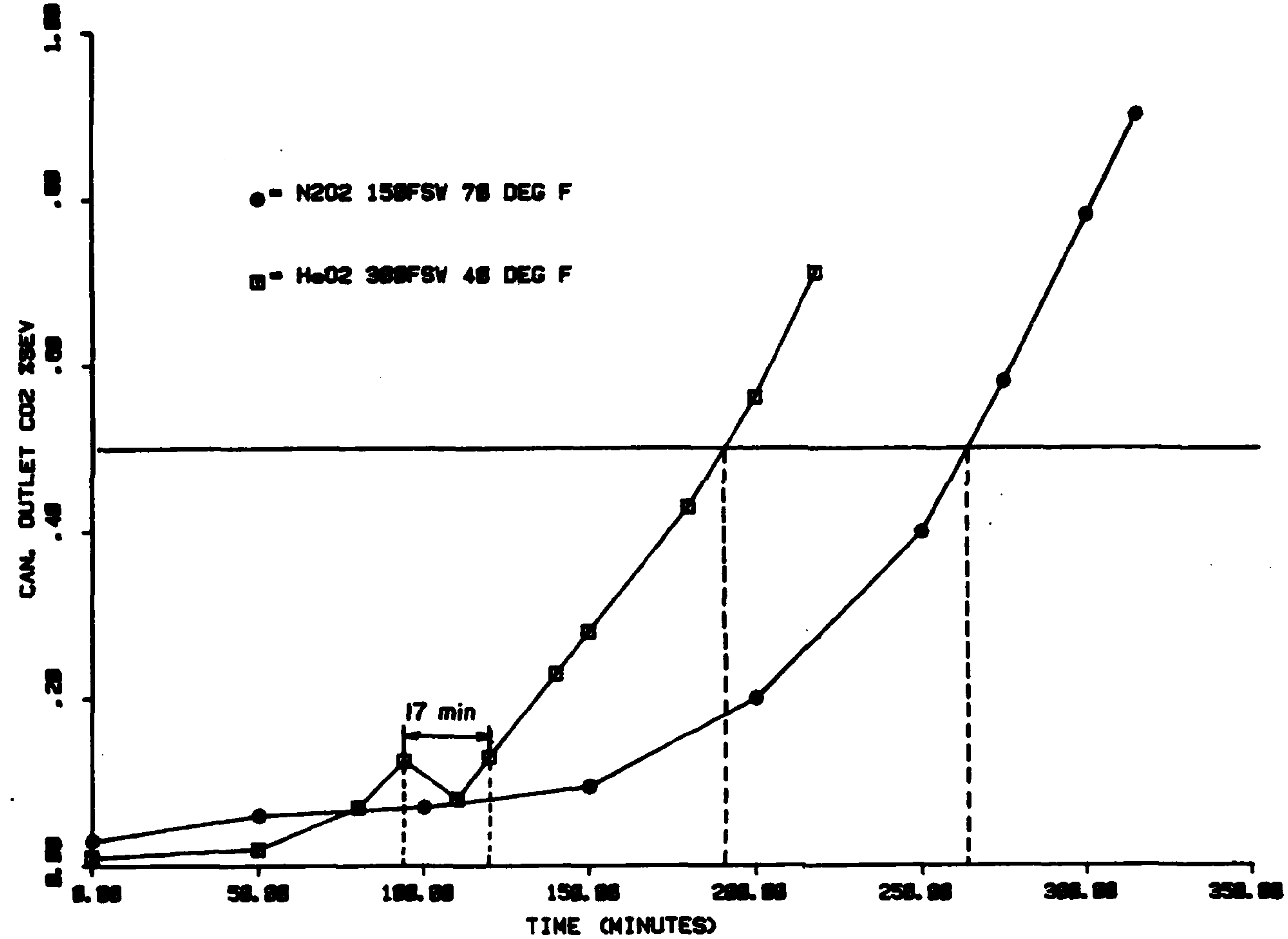


FIGURE 5. ORONASAL PRESSURE RECORDING. DEMONSTRATES STATIC LOAD DURING BREATH HOLD, AND CYCLIC PRESSURE DIFFERENTIAL DURING WORK CYCLE.

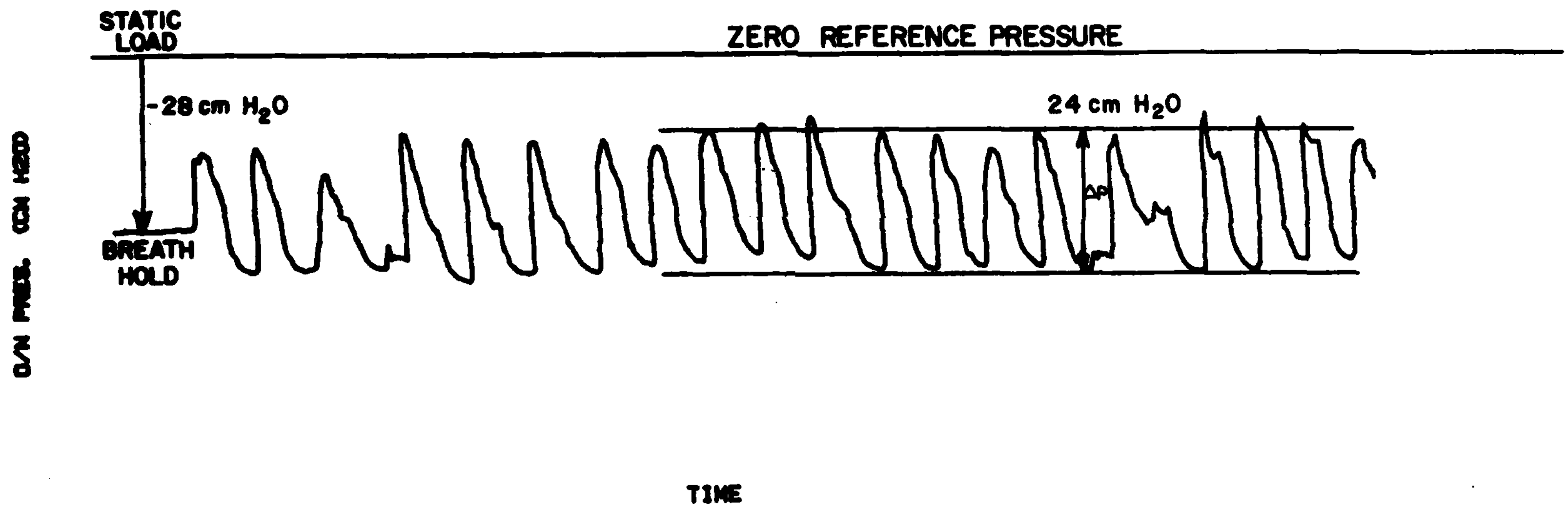
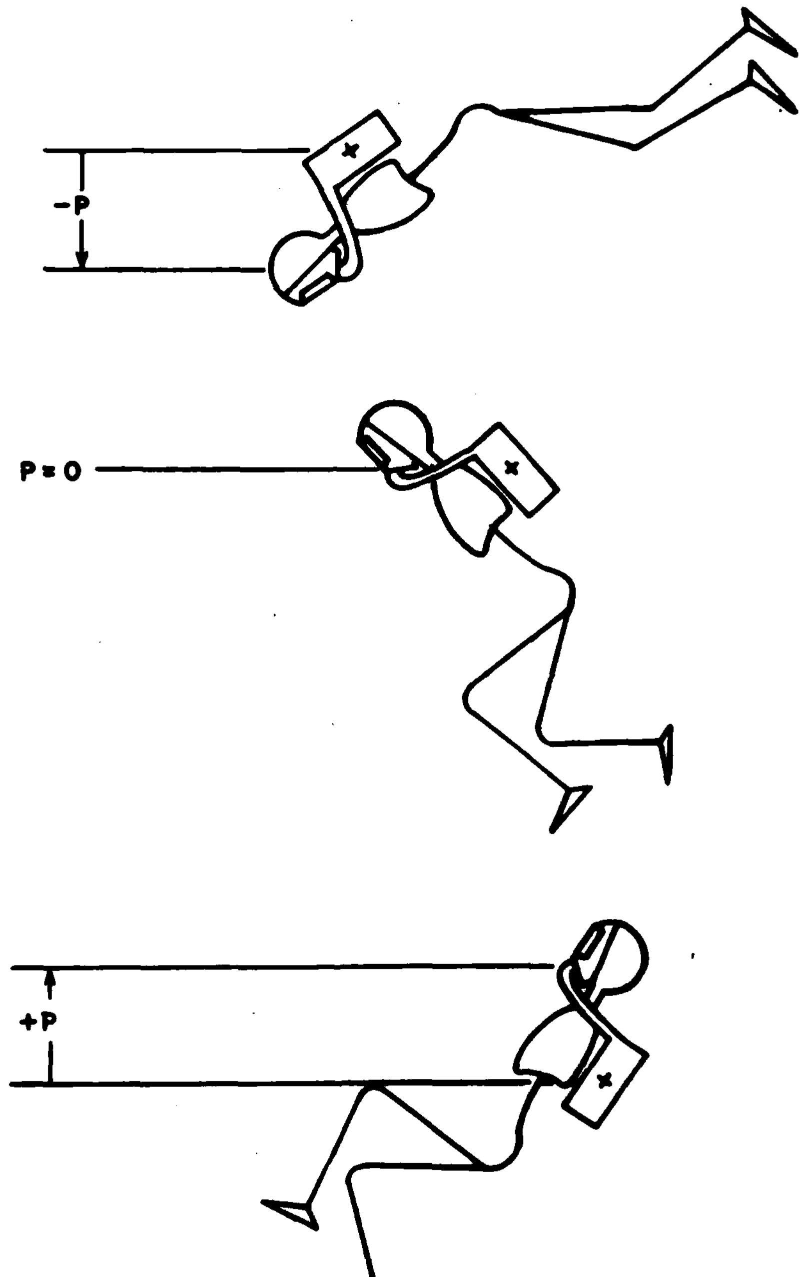


FIGURE 6. SCHEMATIC DEMONSTRATING EFFECT OF CHANGES IN DIVER ATTITUDE ON MASK STATIC LOADING PRESSURE.



P = MASK STATIC
LOADING PRESSURE

FIGURE 7. ORONASAL ΔP VS. $\dot{V}O_2$

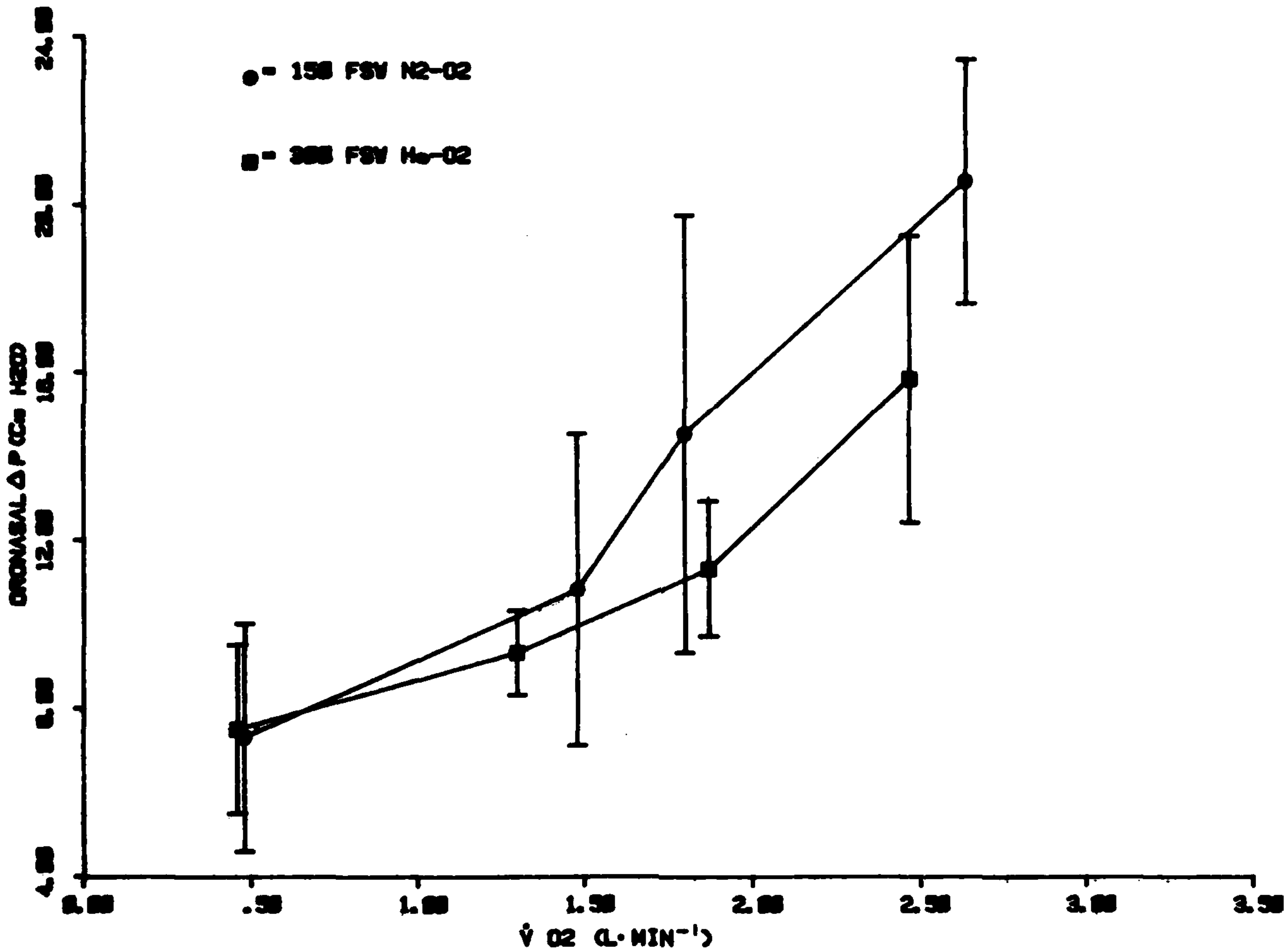


FIGURE 8. END TIDAL P_{CO_2} VS. $\dot{V}_{O_2}$

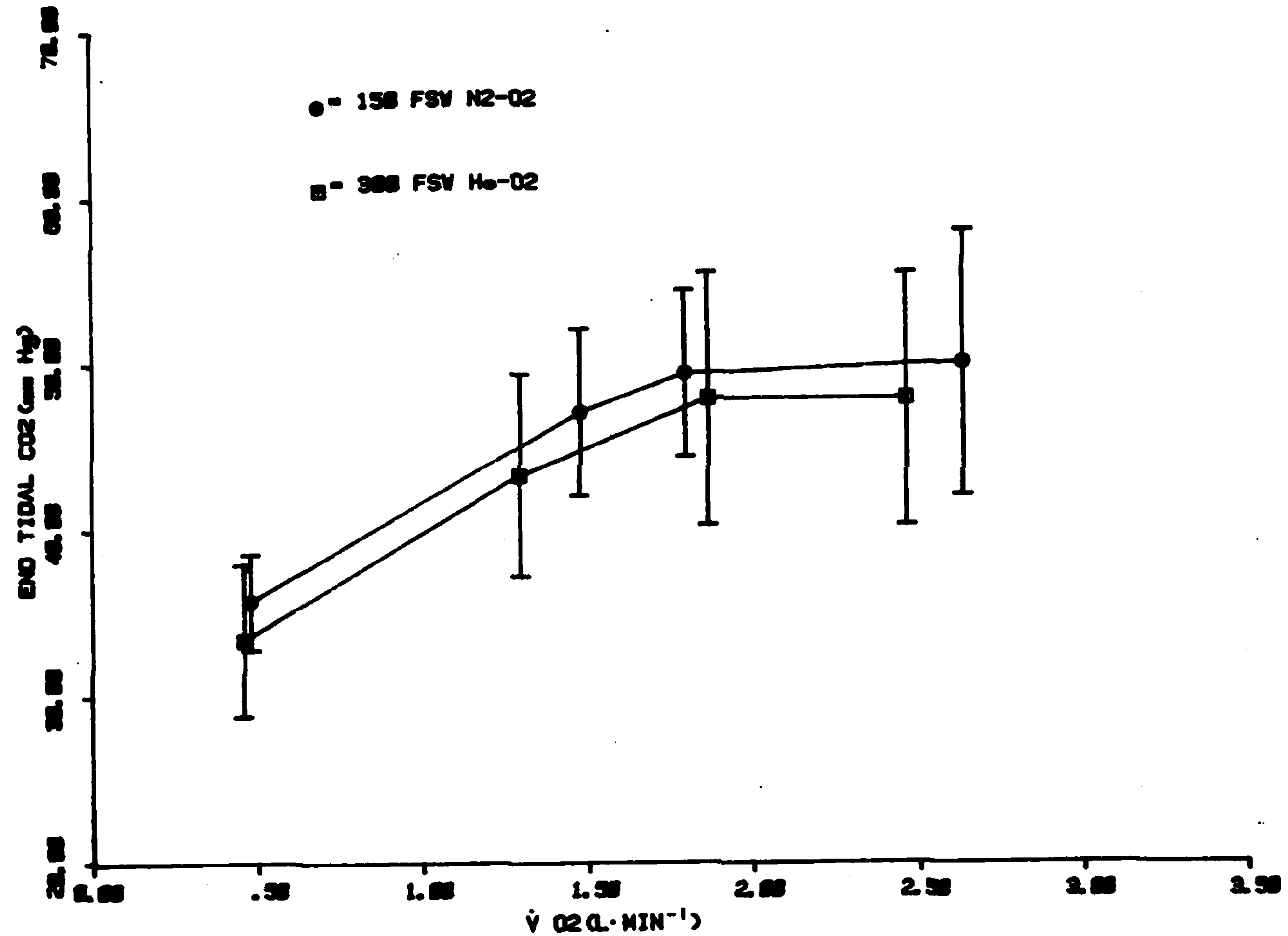
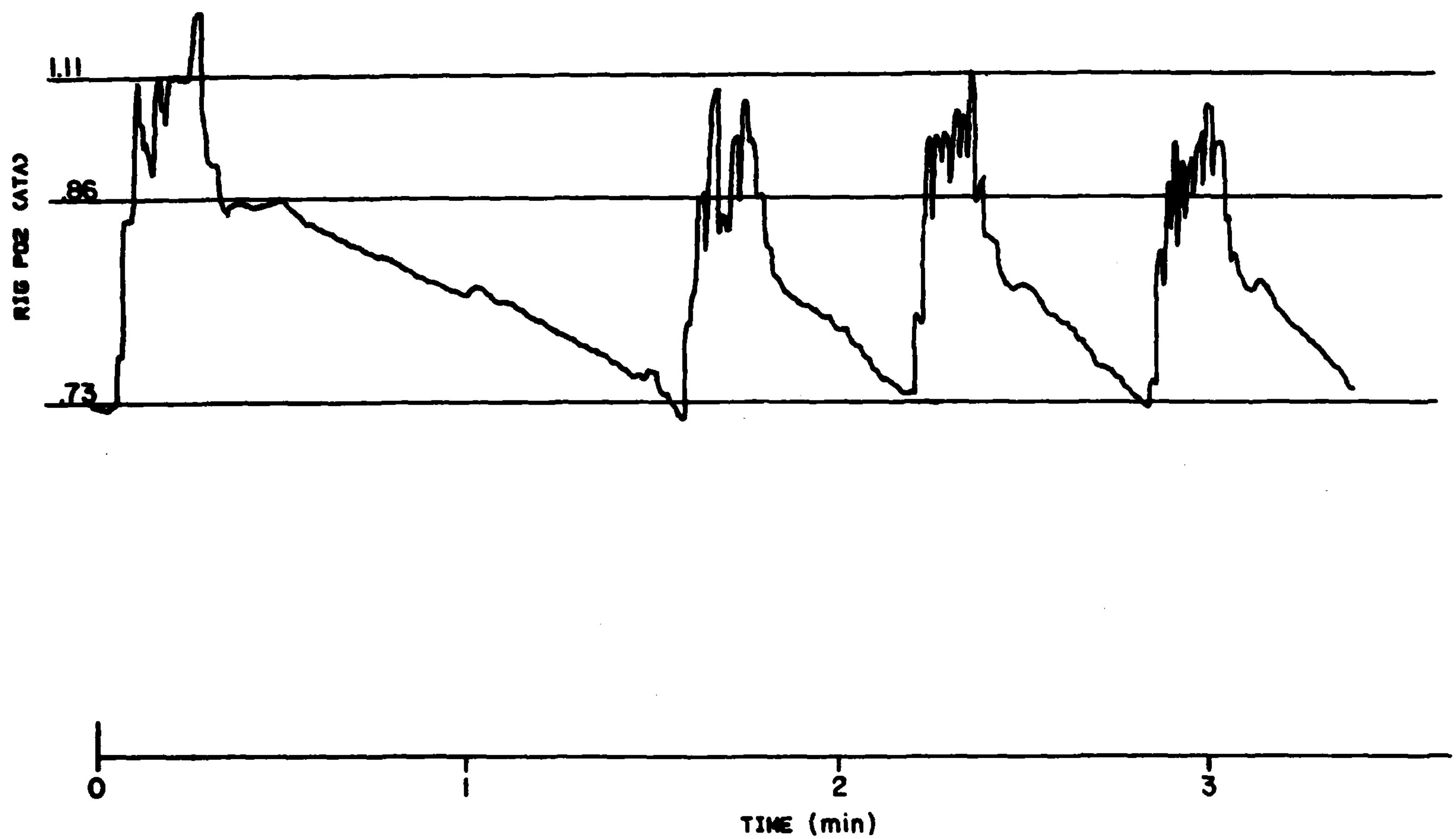


FIGURE 9. DIVER INSPIRED GAS PO_2 RECORDING VS. TIME. NORMAL CYCLIC FUNCTIONAL VARIATION.



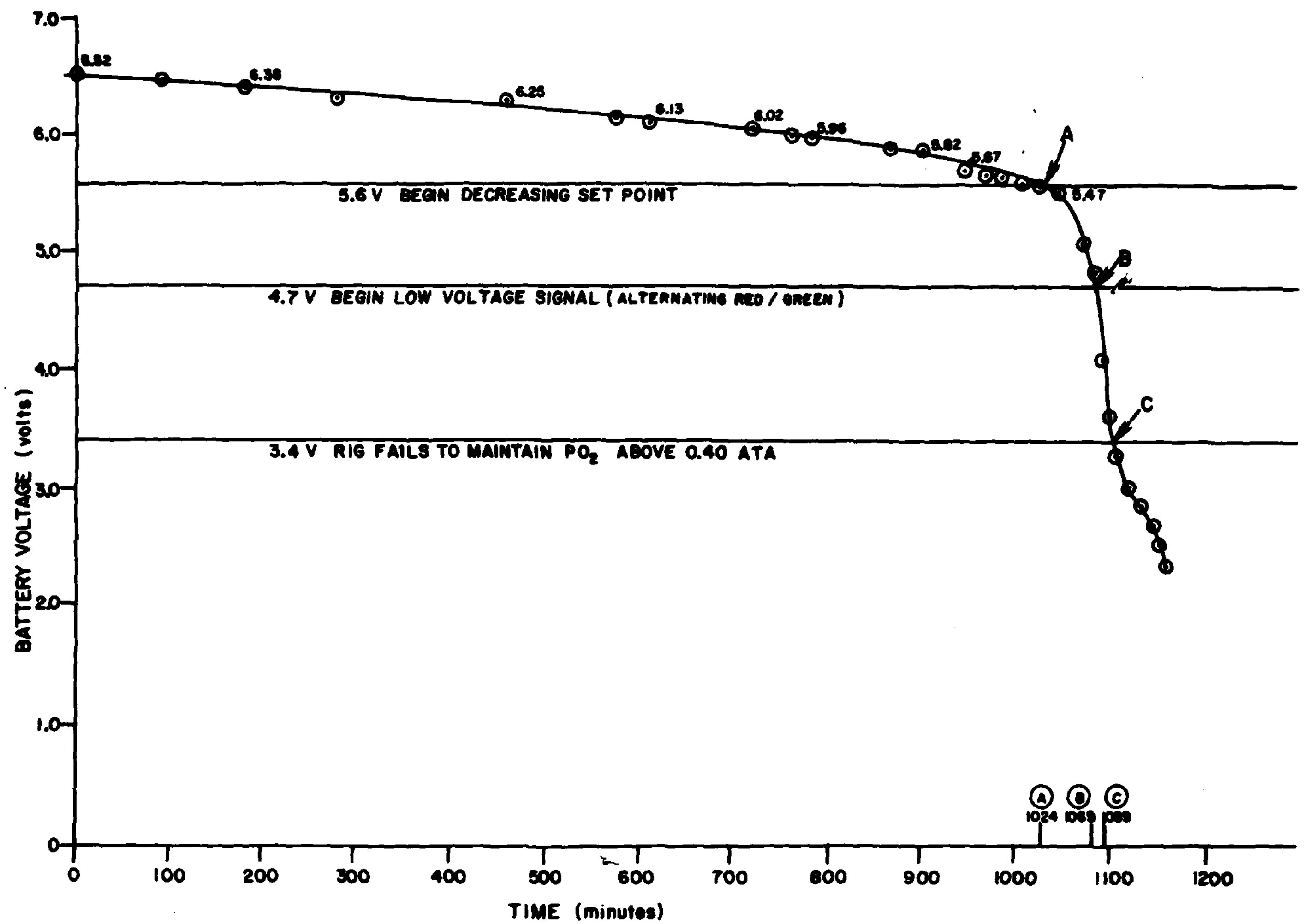


FIGURE 10. BATTERY VOLTAGE DISCHARGE VS. TIME. SINGLE BATTERY DISCHARGED DURING SEVERAL SUCCESSIVE DIVES WITHOUT RECHARGING.

FIGURE 11. DIVER INSPIRED GAS PO_2 RECORDING VS. TIME WITH MALFUNCTION OF O_2 ADDITION VALVE.